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### Recommended Citation

Liaw, Hwee Choo; Oetomo, Denny; Shirinzadeh, Bijan; and Alici, Gursel: Model-based adaptive control of piezoelectric actuation systems 2005, 1-6.  
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# Model-Based Adaptive Control of Piezoelectric Actuation Systems

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**Abstract**— This paper proposes a model-based adaptive control methodology for piezoelectric actuation systems to follow specified motion trajectories. This is motivated by a search for an effective control strategy to deal with the problem of parametric uncertainties such as disturbance and hysteresis effects. The proposed adaptive law is formulated by combining a parameter compensator and a conventional PD feedback control for a system to drive its position tracking error converging to zero. The fundamental concept lies in the properties of a quasi-natural potential function, which allows a saturated position error function in the control formulation. Implementation of the control law requires only the knowledge of initial estimate of the system parameters. Control experiments conducted using the proposed control law on a piezoelectric actuator (PEA) system has demonstrated promising tracking ability in following a specified motion trajectory. Being capable of motion tracking under unknown system parameters and uncertainties due to disturbance and hysteresis, the adaptive control law is very attractive in the field of micro/nano manipulation in which high performance PEA control applications could be realised.

## 1. INTRODUCTION

Micro/nano manipulation has been identified as one of the key enabling technology for many research frontiers, such as: biomedical engineering, micro manufacturing and assembly, nano technology, nano robotics, and micro surgery, to name a few. In achieving these ultra-precision tasks, piezoelectric systems have been identified as an effective means of motion actuation, due to their high stiffness, fast response, and physically unlimited resolution. In recent years, the advancements in piezoelectric actuator (PEA) designs, sensing devices, such as laser interferometry, capacitive sensors, strain gauges, and LVDT, combined with flexure-based mechanisms [1]–[3] have enabled the progress towards the growing area of micro/nano technology.

One major drawback of the PEAs is the presence of highly nonlinear hysteretic behaviour between the input (applied) voltage and the output displacement. This prevents the PEA from providing the desired high-precision motion. A considerable amount of research has been conducted in this area to model and compensate for the hysteresis effect. Some examples include the modelling of physical hysteresis [4], dynamic model of hysteresis for a bi-morph beam [5], a comprehensive voltage-input electromechanical model [6], a differential model of hysteresis and its identification [7],

and a charge steering model that bypasses hysteretic problem coupled with comprehensive model of mechanical dynamics of the PEA [8].

On the other hand, appropriate control strategies can be formulated to take these non-linearities into account to achieve high precision positioning of the PEA systems. Recent examples include a combination of feed-forward model in feedback control with an input shaper [9], an adaptive control using back-stepping approach [10], a PID-based control with iterative learning plus disturbance observer [11], a model-based open loop control [12], and a nonlinear observer-based variable structure control [13]. These control strategies are formulated for specific applications or mechanisms and are usually implemented to track only reference position.

In this paper, a model-based adaptive control methodology is identified and proposed for the PEA systems. This strategy is motivated by the presence of nonlinear behaviour in the PEA system, which makes the exact parameter values of the model difficult to identify. This approach employs the idea of *quasi-natural potential function* [14], which leads to the saturated position error feedback. This potential function possesses the properties that allow us to proof the stability of the formulated control strategy. In this scheme, a parameter compensator is introduced to adjust the control signal to accommodate the unknown system parameters and uncertainties from disturbance including hysteresis effect. The overall adaptive control law is formulated by combining the parameter compensator and a conventional PD feedback control. The stability of the control law is proven theoretically and the controller is able to steer the PEA systems to closely track any desired motion trajectory in position, velocity, and acceleration. Implementation of the system only requires the estimated system parameters.

Control experiments conducted in a PEA system have not only validated the feasibility of the proposed control approach but also shown a promising tracking performance. With the ability to handle unknown system parameters and uncertainties due to disturbance and hysteresis, the proposed adaptive control methodology is very attractive in high performance PEA control applications, through which ultra precision micro/nano-manipulation systems could be

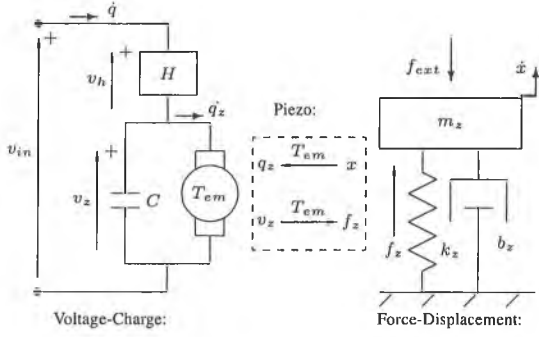


Fig. 1. Schematic model of a piezoelectric actuator (PEA)

realised.

This paper is organized as follows. The model of a piezoelectric actuator is introduced in Section 2. Section 3 describes the properties of a quasi-natural potential function. The formulation of the proposed model-based adaptive control methodology is presented in Section 4 and followed by the stability analysis in Section 5. The experimental study is detailed in Section 6 and the results are shown and discussed in Section 7. Finally, conclusions are drawn in Section 8.

## 2. MODEL OF PIEZOELECTRIC ACTUATOR

An electromechanical model of a PEA is given in [6], [8]. This mathematical model can be divided into three stages of transformation from electrical to mechanical energy, and vice versa. The schematic model as shown in Fig. 1 illustrates the transformation, which consists of voltage-charge, piezo, and force-displacement stages.

Note that the model in Fig. 1 is formulated for a voltage-controlled amplifier. The dynamic equation from the electrical input to the output motion stage can be described by the following set of equations:

$$v_{in} = v_h + v_z, \quad (1)$$

$$v_h = H(q), \quad (2)$$

$$q = C v_z + q_z, \quad (3)$$

$$q_z = T_{em} x, \quad (4)$$

$$f_z = T_{em} v_z, \quad (5)$$

$$m_z \ddot{x} + b_z \dot{x} + k_z x = f_z - f_{ext}, \quad (6)$$

where  $v_{in}$  represents the applied (input) voltage,  $v_h$  is the voltage due to hysteresis,  $v_z$  is the voltage related to mechanical side of the actuator,  $q$  is the total charge in the ceramic,  $H$  is the hysteresis effect,  $C$  is the linear capacitance connected in parallel with the electromechanical transformer having a ratio of  $T_{em}$ ,  $q_z$  is the piezo charge related to the actuator output displacement  $x$ ,  $f_z$  is the transduced force from the electrical domain,  $m_z$ ,  $b_z$ , and  $k_z$  are the mass, damping, and stiffness, respectively, of the mechanical stage, and  $f_{ext}$

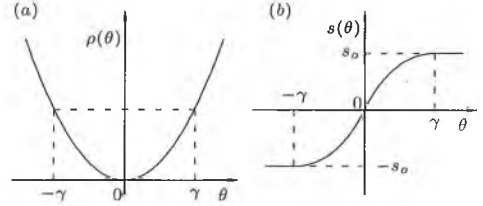


Fig. 2. (a) Quasi-natural potential,  $\rho(\theta)$ , and (b) its derivative,  $s(\theta)$

is the force imposed by the external mechanical load. In PEA, hysteresis causes a highly nonlinear input/output relationship between the applied voltage and displacement. Goldfarb and Celanovic [6] described the hysteresis effect as a nonlinear charge-dependent phenomenon and noted that it appeared only in the electrical domain.

For control purposes, (1) and (5) are substituted into (6) to yield

$$m_z \ddot{x} + b_z \dot{x} + k_z x = T_{em} (v_{in} - v_h) - f_{ext}, \quad (7)$$

and the PEA model is obtained by re-arranging the above,

$$m \ddot{x} + b \dot{x} + k x + v_h + f_e = v_{in}, \quad (8)$$

where  $m = m_z / T_{em}$ ,  $b = b_z / T_{em}$ ,  $k = k_z / T_{em}$ , and  $f_e = f_{ext} / T_{em}$ .

## 3. QUASI-NATURAL POTENTIAL FUNCTION

Consider a quasi-natural potential function,  $\rho(\theta)$ , as shown in Fig. 2 for formulating the control methodology. This potential function is assumed to have the following conditions [14]:

- 1)  $\rho(\theta) > 0$  for  $\theta \neq 0$  and  $\rho(0) = 0$ ;
- 2)  $\rho(\theta)$  is twice continuously differentiable, and the derivative,  $s(\theta) = d\rho(\theta)/d\theta$ , is strictly increasing in  $\theta$  for  $-\gamma < \theta < \gamma$  and saturated for  $|\theta| \geq \gamma$ , i.e.  $s(\theta) = \pm s_0$  for  $\theta \geq \gamma$  and  $\theta \leq -\gamma$ , respectively;
- 3) there are constants  $c_1 > 0, c_2 > 0$  such that for  $\theta \neq 0$

$$\rho(\theta) \geq c_1 s^2(\theta) > 0, \quad (9)$$

$$\theta s(\theta) \geq c_2 s^2(\theta) > 0. \quad (10)$$

Additional properties can also be observed:

- 4) the second derivative,  $\varrho(\theta) = ds(\theta)/d\theta$ , is such that
$$\varrho(\theta) \geq 0 \quad \forall \quad \theta; \quad (11)$$
- 5) the rate of change of  $s(\theta)$ ,  $\dot{s}(\theta) = \varrho(\theta) \dot{\theta}$ , will lead to
$$\dot{s}(\theta) \dot{\theta} = \varrho(\theta) \dot{\theta}^2 \geq 0; \quad (12)$$
- 6) there are constants  $c_3^+ > 0, c_3 > 0, c_3^+ > c_3$  such that for  $\varrho(\theta) \neq 0$  and  $\dot{\theta} \neq 0$ 

$$c_3^+ \dot{\theta}^2 \geq \dot{s}(\theta) \dot{\theta} \geq c_3 \dot{\theta}^2 > 0. \quad (13)$$

Examples of the quasi-natural potential functions can be found in [14] and [15].

#### 4. MODEL-BASED ADAPTIVE CONTROL

The control problem of tracking a desired motion trajectory,  $x_d(t)$ , can be formulated by designing a model-based adaptive control methodology for the PEA system described by (8). Under the proposed control approach, the physical parameters of the system in (8) are assumed to be unknown or uncertain. The  $x_d(t)$  is assumed to be twice continuously differentiable and both  $\dot{x}_d(t)$  and  $\ddot{x}_d(t)$  are bounded and uniformly continuous in  $t \in [0, \infty)$ . A parameter compensator and a conventional PD feedback control are employed in the control law so that the closed loop system will follow the required trajectory  $x_d(t)$ .

To derive the control law, the PEA model of (8) is rewritten in terms of a set of physical parameters,  $\varphi = [m, b, k, v_h]^T$ , and the PEA model becomes

$$x^T \varphi + f_e = v_{in}, \quad (14)$$

where  $x = [\ddot{x}, \dot{x}, x, 1]^T$ . A set of estimated parameters,  $\hat{\varphi}$ , of  $\varphi$  is defined as

$$\hat{\varphi} = [\hat{m}, \hat{b}, \hat{k}, \hat{v}_h]^T, \quad (15)$$

such that a parameter compensator,  $\hat{\varphi}(t)$ , is introduced to continuously update the control system through

$$\hat{\varphi}(t) = \hat{\varphi}(0) - \int_0^t K^{-1} x_d y(\tau) d\tau, \quad (16)$$

where  $\hat{\varphi}(0)$  is the initial estimate of  $\varphi(t)$  at  $t = 0$ ,  $K$  is a  $4 \times 4$  constant positive definite diagonal matrix,  $x_d = [\ddot{x}_d, \dot{x}_d, x_d, 1]^T$ , and  $y(t)$  is defined as

$$y = \dot{e}_p + \alpha s(e_p), \quad (17)$$

where  $e_p(t) = x(t) - x_d(t)$ ,  $\alpha$  is a positive scalar, and  $s(e_p)$  is the saturated position error function,  $s(e_p) = d\rho(e_p)/de_p$ , described in Section 3. An estimated control signal,  $\hat{v}_{in}$ , can therefore be established by

$$\hat{v}_{in} = x_d^T \hat{\varphi}. \quad (18)$$

The proposed model-based adaptive control input is given as

$$v_{in} = -k_p e_p - k_v \dot{e}_p + \hat{v}_{in} + f_e, \quad (19)$$

where  $k_p$  and  $k_v$  are the proportional and derivative gains, respectively.

The control structure of the proposed model-based adaptive control methodology for the PEA system is summarised in Fig. 3.

#### 5. STABILITY ANALYSIS

To study the closed loop stability under the proposed control methodology, the dynamics of the closed loop system must be examined. From that, the error dynamics of the system can be derived and used in the stability analysis of the closed loop system.

To examine the closed loop dynamics of the system, the control input (19) is substituted into the PEA model (14) and using (18) to eliminate  $\hat{v}_{in}$ ,

$$x^T \varphi = -k_p e_p - k_v \dot{e}_p + x_d^T \hat{\varphi}. \quad (20)$$

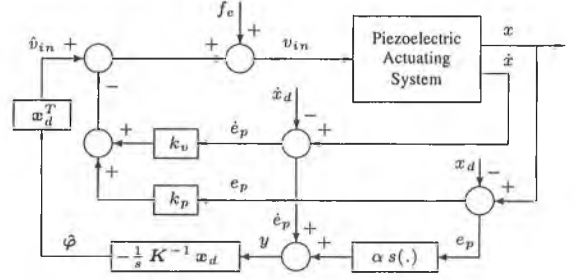


Fig. 3. Model-based adaptive control methodology

An estimated control error,  $\Delta v$ , due to the parameter compensator can be derived as

$$\Delta v = x_d^T \Delta \varphi, \quad (21)$$

where

$$\Delta \varphi = \hat{\varphi} - \varphi, \quad (22)$$

and (21) can be re-written as

$$\Delta v = x_e^T \varphi - x^T \varphi + x_d^T \hat{\varphi}, \quad (23)$$

where  $x_e = x - x_d = [\ddot{e}_p, \dot{e}_p, e_p, 0]^T$ . Noticing the closed loop dynamics in (20), the estimated control error (23) becomes

$$\Delta v = x_e^T \varphi + k_p e_p + k_v \dot{e}_p, \quad (24)$$

which is the error dynamics of the closed loop system.

For the purpose of stability analysis, the error dynamics in (24) is multiplied by (17),

$$\Delta v y = [x_e^T \varphi + k_p e_p + k_v \dot{e}_p] [\dot{e}_p + \alpha s(e_p)]. \quad (25)$$

Expanding the right-hand side of (25),

$$\begin{aligned} \text{RHS} &= m \ddot{e}_p \dot{e}_p + (b + k_v) \dot{e}_p^2 + (k + k_p) e_p \dot{e}_p + \\ &\quad [m \ddot{e}_p + (b + k_v) \dot{e}_p + (k + k_p) e_p] \alpha s(e_p), \\ &= \frac{du_1}{dt} + w, \end{aligned} \quad (26)$$

where

$$u_1 = \frac{1}{2} m \dot{e}_p^2 + \alpha (b + k_v) \rho(e_p) + \frac{1}{2} (k + k_p) e_p^2 + \alpha m s(e_p) \dot{e}_p, \quad (27)$$

$$w = (b + k_v) \dot{e}_p^2 + \alpha (k + k_p) e_p s(e_p) - \alpha m \dot{s}(e_p) \dot{e}_p, \quad (28)$$

where  $\rho(e_p)$  is the quasi-natural potential function described in Section 3. Re-write  $u_1$  in (27) as

$$\begin{aligned} u_1 &= \frac{1}{4} [\dot{e}_p + 2\alpha s(e_p)] m [\dot{e}_p + 2\alpha s(e_p)] + \frac{1}{4} m \dot{e}_p^2 - \\ &\quad \alpha^2 m s^2(e_p) + \alpha (b + k_v) \rho(e_p) + \\ &\quad \frac{1}{2} (k + k_p) e_p^2. \end{aligned} \quad (29)$$

Using (9) for  $\rho(e_p)$  in above equation,

$$u_1 \geq \frac{1}{4} m [\dot{e}_p + 2\alpha s(e_p)]^2 + \frac{1}{4} m \dot{e}_p^2 + \alpha [-\alpha m + c_1 (b + k_v)] s^2(e_p) + \frac{1}{2} (k + k_p) e_p^2. \quad (30)$$

Thus,  $u_1$  is always positive if the control gains,  $k_p$  and  $k_v$ , in (19) are chosen as

$$\begin{aligned} k_p &> -k, \\ k_v &> \frac{\alpha m}{c_1} - b. \end{aligned} \quad (31)$$

Using (10) and (13) for  $e_p s(e_p)$  and  $\dot{s}(e_p) \dot{e}_p$ , respectively, in (28), and the constants,  $c_2$  and  $c_3^+$ , are selected in such a way that

$$\begin{aligned} w &\geq (b + k_v) \dot{e}_p^2 + c_2 \alpha (k + k_p) s^2(e_p) - c_3^+ \alpha m \dot{e}_p^2, \\ &\geq (b + k_v - c_3^+ \alpha m) \dot{e}_p^2 + c_2 \alpha (k + k_p) s^2(e_p). \end{aligned} \quad (32)$$

To assure a positive  $w$ , the control gains in (19) must be selected so that

$$\begin{aligned} k_p &> -k, \\ k_v &> c_3^+ \alpha m - b. \end{aligned} \quad (33)$$

It is possible that the left-hand side of (25) can be related to a positive function. Consider a positive function  $u_2$  given as

$$u_2 = \frac{1}{2} \Delta \varphi^T K \Delta \varphi. \quad (34)$$

Differentiating  $u_2$  with respect to time yields

$$\frac{du_2}{dt} = \Delta \varphi^T K \Delta \dot{\varphi}. \quad (35)$$

Due to the fact that the parameters,  $\varphi$ , of system (14) are time-invariant, i.e.  $\dot{\varphi} = 0$ ,

$$\Delta \dot{\varphi} = \dot{\varphi} - \dot{\varphi} = \dot{\varphi}, \quad (36)$$

the term  $\dot{\varphi}$  can be obtained from (16) as

$$\dot{\varphi} = -K^{-1} x_d y. \quad (37)$$

Substituting (37) into (35),

$$\begin{aligned} \frac{du_2}{dt} &= \Delta \varphi^T K [-K^{-1} x_d y], \\ &= -[x_d^T \Delta \varphi]^T y, \\ &= -\Delta v y, \end{aligned} \quad (38)$$

where the scalar  $\Delta v$  is defined in (21).

*Theorem:* For the PEA system described by (8), the model-based adaptive control law (19) and the parameter compensator (16) assert the convergence of motion trajectory tracking with  $e_p(t) \rightarrow 0$  and  $\dot{e}_p(t) \rightarrow 0$  as  $t \rightarrow \infty$  under the conditions of (31) and (33).

*Proof:* In the closed loop system formed by the system described by (8), the control law (19), and the parameter compensator (16), the functions,  $u_1$  and  $w$ , from (27) and (28), respectively, are always positive in  $e_p(t)$  and  $\dot{e}_p(t)$

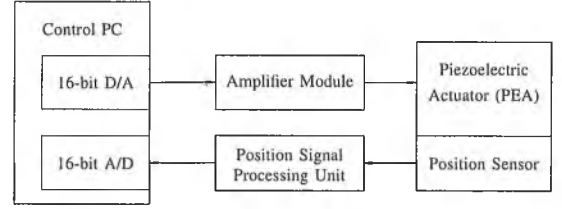


Fig. 4. Block diagram of PEA experimental system

under the conditions of (31) and (33). Furthermore, the function  $u_2$  is chosen to be positive in (34). A continuous and non-negative Lyapunov function  $u$  can therefore be proposed as

$$u = u_1 + u_2. \quad (39)$$

The time derivative of  $u$  can be obtained by combining (25), (26), and (38) as

$$\frac{d}{dt}(u_1 + u_2) = -w, \quad (40)$$

which shows that  $u \rightarrow 0$  and implies  $e_p(t) \rightarrow 0$  and  $\dot{e}_p(t) \rightarrow 0$  as  $t \rightarrow \infty$ . Both system stability and tracking convergence are guaranteed by the control law (19) and the parameter compensator (16) driving the system (8) following the desired motion trajectory,  $x_d(t)$ , closely. ■

## 6. EXPERIMENTAL STUDY

In the process of developing a micro/nano manipulation system using the PEAs, a single-axis of PEA is set up for the experimental study of the proposed control strategy. The experimental system is shown in Fig. 4, which consists of a PEA with position sensor, an amplifier module, a position signal processing unit, and a control PC installed with a digital-to-analogue (D/A) and an analog-to-digital (A/D) boards. The PEA employed is a PI (Physik Instrumente) multilayer PZT stacked ceramic translator, model P-843.30, capable of expansion up to 45  $\mu m$  corresponding to a range of operating voltage up to maximum of 100 V. The PEA is preloaded 300 N by an internally spring and is incorporated with an ultra-high-resolution strain gauge sensor for position feedback. The amplifier module is a PI model E-505.00 with a fixed output gain of 10 providing voltage ranges from -20 to +120 V. The position signal processing unit is housed in a PI servo controller, model E-509-X3. The PI servo controller is disabled and only the signal processing unit is used to interface with the PEA position sensor. A standard desktop computer is used as the control PC. It is equipped with a Pentium 4 2.8 GHz processor running on an operating system capable of hard real-time control. Both the D/A and A/D boards installed in the control PC are of 16-bit resolution. They are used for generating the control signal and reading the analog position, respectively. In the control experiments, the sampling frequency of the control loop is set at 2.5 kHz.

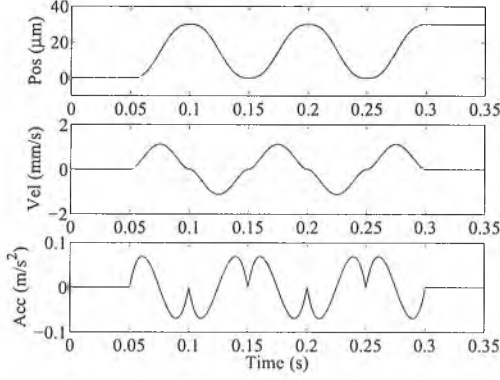


Fig. 5. Desired motion trajectory

The control experiments serve not only to validate the theoretical formulation of the control algorithm but also to examine the effectiveness of the proposed scheme in a physical PEA system. In the experimental study, the closed loop system is required to follow a desired motion trajectory, which is shown in Fig. 5 for position, velocity, and acceleration, respectively. The desired motion trajectory is quintic polynomial [16] and made up of different segments to analyse the tracking and steady-state performances of the system.

For the PEA system described in (8), the parameter compensator (16) and the control law (19) are implemented in the PC. With the desired motion trajectory, the tracking ability of the control system can be closely examined when it is subjected to uncertain parameters including unknown disturbance and hysteresis effects.

As mentioned, the proposed control law (19) consists of a parameter compensator and a conventional PD feedback control. To study the effect of the adaptive component, a PD feedback control is implemented for comparison by omitting the adaptive component,  $\hat{v}_{in}$ , in (19), i.e.

$$v_{in} = -k_p e_p - k_v \dot{e}_p + f_e. \quad (41)$$

In the control experiment, the initial estimate,  $\hat{\varphi}(0)$ , in (16) is chosen to be zero. The control gains,  $k_p$  and  $k_v$ , in (19) are tuned as

$$k_p = 4 \times 10^6 \text{ V/m} \quad \text{and} \quad k_v = 1 \times 10^3 \text{ Vs/m}. \quad (42)$$

It is assumed that no external force is applied to the system and the term  $f_e$  in (19) is set to zero in the control experiment. Furthermore, the diagonal constant matrix  $\mathbf{K}$  in (16) is selected as

$$\mathbf{K}^{-1} = 2 \times 10^6 \text{ diag}\{1, 1, 1\}, \quad (43)$$

where the units of  $\mathbf{K}^{-1}$  are  $\text{Vs}^4/\text{m}^3$ ,  $\text{Vs}^2/\text{m}^3$ ,  $\text{V}/\text{m}^3$ , and  $\text{V}/\text{m}$ , respectively. The positive scalar,  $\alpha$ , in (17) is set at  $\alpha = 1 \text{ s}^{-1}$ , and the saturated position error function,  $s(e_p)$ ,

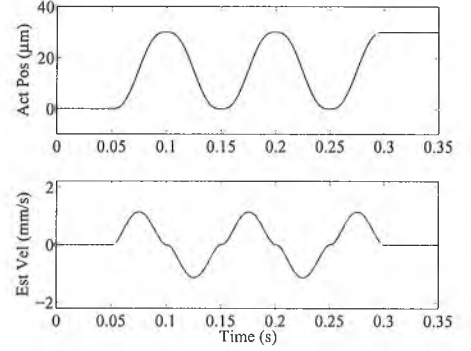


Fig. 6. Adaptive scheme: Actual position and estimated velocity

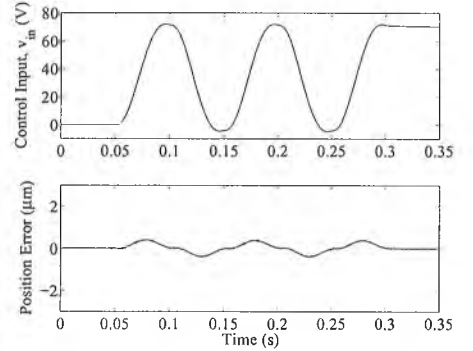


Fig. 7. Adaptive scheme: Control input and position tracking error

in (17) is implemented as

$$s(e_p) = \begin{cases} e_s & : e_p > e_s, \\ e_s \sin \frac{\pi e_p}{2 e_s} & : -e_s \leq e_p \leq e_s, \\ -e_s & : e_p < -e_s, \end{cases} \quad (44)$$

where  $e_s$  is the specified position error, which is chosen as  $e_s = 1 \mu\text{m}$ .

For comparison, the PD control in (41) is implemented using the same control gains as given in (42).

## 7. RESULTS AND DISCUSSION

The experimental results of the model-based adaptive control methodology are shown in Fig. 6 and Fig. 7. From the desired motion trajectory as shown in Fig. 5, the PEA is commanded to travel in a range of  $30 \mu\text{m}$  with maximum velocity and acceleration reaching  $1.1 \text{ mm/s}$  and  $0.07 \text{ m/s}^2$ , respectively. The resulting PEA position and the estimated velocity are shown in Fig. 6. Despite system uncertainties and zero initial conditions for the parameter compensator (16), the adaptive control law (19) is shown to be stable with the control input to the PEA as shown in Fig. 7. Furthermore, from the position tracking error, as presented in Fig. 7, the closed loop system tracks the desired motion trajectory with position tracking error within  $0.45 \mu\text{m}$  during motion and less than  $0.03 \mu\text{m}$  at steady-state, which is almost at the noise level of the closed loop system. Note that the resulting

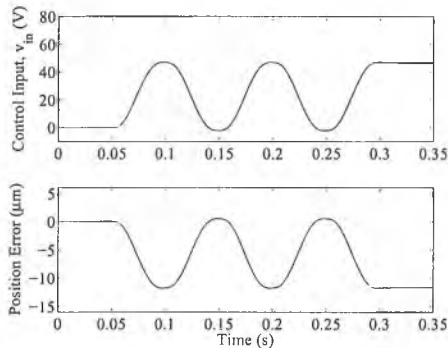


Fig. 8. PD scheme: Control input and position tracking error

position tracking error is within the specified position error,  $1\ \mu m$ , described in (44).

In comparison, the control results of the PD control, as shown in Fig. 8, indicate that the PD control does not provide enough actuating voltage to the PEA. The PD control results in relatively large position tracking error, which is more than  $11\ \mu m$ . On the other hand, this implies that the adaptive component of the proposed control approach is effective and it plays an important role in the tracking performance.

On the whole, the model-based adaptive control methodology, combining a conventional PD control and a parameter compensator, is shown to be stable, robust, and capable of following the desired motion trajectory under unknown system parameters and other uncertainties. Good control results are achieved even with the initial estimate,  $\hat{\varphi}(0)$ , set to zero for the parameter compensator (16) in the above implementation. However, some effort is needed to tune the system for the desirable control performance.

## 8. CONCLUSIONS

A model-based adaptive control methodology was proposed for piezoelectric actuation systems to follow a set of specified motion trajectories. In this approach, a parameter compensator was employed and combined with a conventional PD feedback control in formulating the proposed adaptive scheme for a control system to drive its position tracking error converging to zero.

The fundamental concept in the adaptive control law lies in the properties of a quasi-natural potential function. With these properties, a saturated position error function is allowed in the parameter compensator and the stability of the overall control scheme is proven theoretically.

Implementation of the adaptive control law requires only the knowledge of the estimated system parameters for the initial conditions of the parameter compensator. However, proper tuning of the system is required to achieve a desired control performance.

Control experiments were conducted on a PEA system for tracking a specified quintic motion trajectory. The adaptive control law was demonstrated to possess promising tracking ability. Compared to the adaptive control, the conventional

PD scheme performed poorly without the adaptive compensation.

Being capable of motion tracking under unknown system parameters and uncertainties due to disturbance and hysteresis, the adaptive control methodology is very attractive in the field of micro/nano-manipulation in which high performance PEA control applications could be implemented.

## ACKNOWLEDGMENT

This work is supported by ARC LIEF grant, ARC Discovery grant, and Monash Research Fund.

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